Safeguarding of the Portuguese Heritage: the Case Study of Safi Cathedral, Morocco

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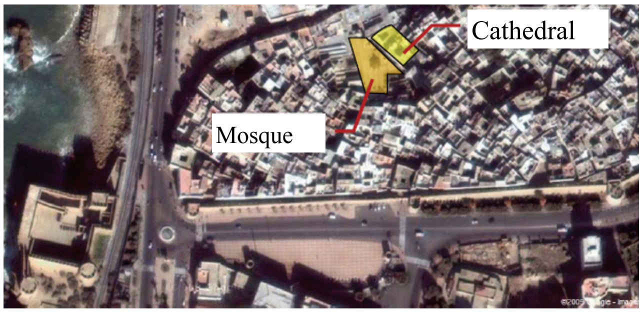
ABSTRACT: The city of Safi is located in the West African coast, about 150 km from the city of Marrakesh and 300 km south of Casablanca, Morocco. The Cathedral of Safi was the first Portuguese cathedral outside Portugal during the Expansion period and it is the most important example of the non-military Manueline architecture that still remains outside Portugal. The construction of the cathedral started during the decade of 1520. It was originally a three nave church and is believed to be similar to other temples of the time such as the Funchal or Guarda Cathedrals. During its history, the cathedral was occupied by Muslims who eliminated the naves, leaving only the main altar, one lateral chapel and an outside wall. The space of the naves was used to add several residential buildings and they turned the altar in a bathhouse for women (hammam in Arab). The altar, crowned by a ribbed vault, the lateral chapel whose roof, also vaulted, is missing and one alone standing external wall are the only original parts of the structure that are left. The Cathedral will be soon submitted to a structural intervention. The intervention includes the preservation of the original remains of the Cathedral, the correction of existing problems in the structure, improvement and installation of new infrastructure to support tourism and cultural events. Therefore, safety conditions and the conservation of the built heritage as a museum space must be assured.

INTRODUCTION

The city of Safi is located in the West African coast, about 150 km from the city of Marrakesh and 300 km south of Casablanca, Morocco. The main economic activities of this city correspond to fishing and exportation of phosphate, textiles and ceramics. Figure 1a shows its location.

(a)



(b)

Figure 1: Safi Cathedral location: (a) Morocco map; and (b) location of the Safi Cathedral in the Medina.

During the 15th C., Safi was an important trading port. Between the years 1488 and 1541, the city was governed by Portuguese and became the name of Safim. Amongst the Portuguese constructions from the Manueline period which still remain and stand out are the Cathedral of Safi, the Castle of the Sea and the Fortress of Safi.

The Cathedral of Safi was the first cathedral constructed beyond Portuguese borders. Similarities with other Portuguese cathedrals constructed during that period, such as the cathedral of Funchal or Guarda [1], can be admitted. This cathedral is located in midst of the Medina of the Safi, by side of the Great Mosque, as can be seen in Figure 1b.

The Cathedral of Safi was constructed around 1520 by Master-builder João Luís under the promotion of archbishop D. João Subtil. The Cathedral was occupied by Muslims, which transformed the space of the main altar into a hammam. The vault of the main chapel (with exception of constructions of the military field), remains the best example of the Manueline architecture subsisting outside Portugal [1].

Following the departure of the Portuguese in 1541 and the ascension to power of Sultan Cheikh, the Mosque was largely enhanced in a place of high historical, religious and social value for the city of Safi.

THE SAFI CATHEDRAL

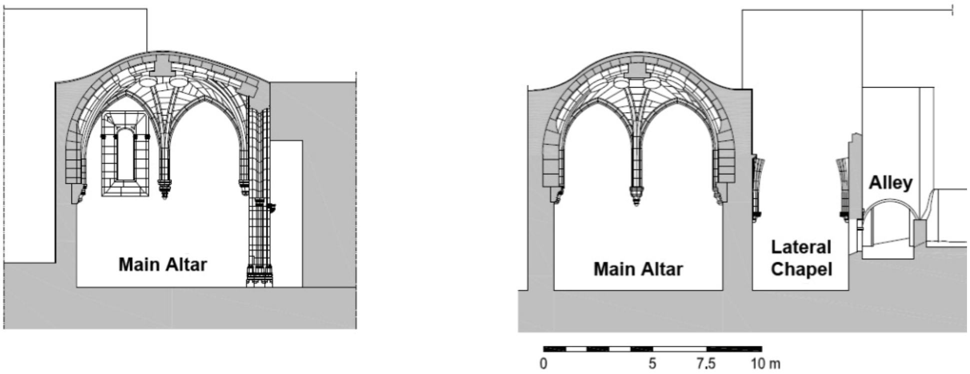
The remaining structure of the Safi Cathedral is the main chapel, the right lateral chapel and an exterior wall. The main chapel is almost squared and is crowned by a ribbed vault. Its dimensions are approximately 8.2 × 7.8 m width in plant, with a maximum height of 9.7 m measured from the existing pavement to the center of the vault. The lateral chapel is also rectangular with approximately 4.5 × 5.4 m width. This part of the structure is exposed to the outside on its upper part, since its roof cover does not exist anymore. The remaining walls are 6.9 m high. The external wall is 15.1 m long, 0.9 m thick and 9.6 m high (from the inside).

Because the cathedral was built in the same period as the Funchal cathedral, it is believed that the Safi Cathedral had a similar structural organization. In this case, the Safi cathedral would have been an arrangement of three naves and two lateral chapels, covered by a light wooden roof. Figure 2a shows the actual structural configuration of the remaining Cathedral (colored areas), the adjacent structures and the probable original configuration is presented in Figure 2b. A brief description of the Funchal cathedral is given in the next Section, in order to give the reader an idea of how the original Safi Cathedral may have looked like.

(a) (b)

Figure 2: Plant of Cathedral [2]: (a) Plant of street level of the existing structures; (b) Possible former outline of the original Cathedral.

Figure 3 shows an elevation of the original remains of the main chapel with its ribbed vault, and the lateral chapel, now without vault. It also can be appreciated in this figure, that the level of the alley is 1.4 m higher than the pavement of the Cathedral. This is very usual in old cities, since the cities have been built progressively over time. Therefore, streets and alleys are mainly composed of infill material which has accumulated over centuries. Finally, these old streets and alleys can be up to some meters over the level of the former ground floors.



(a) (b)

Figure 3: Elevations of Cathedral: (a) Elevation of main chapel in north-east direction; and (b) elevation of main chapel and lateral chapel in south-east direction.

Figure 4 shows some general views of the inside of the Manueline ruins [2]. As it can be observed in Figure 4a, the structure is made of two types of stone masonry. The walls are in general of masonry with limestone units and lime mortar joints. Nevertheless, several joints with cement mortar could be observed, which correspond to recent reparation works. The vault of the main chapel has ribs made of local stone with joints of poor lime mortar. The remaining wall corresponds to porous limestone.

(a) (b) (c)

Figure 4: Main chapel: (a) elevation in south-west direction; (b) inner view in south-west direction (former hammam); and (c) detail of encounter of pointed arch, diagonal rib and partition wall of south west elevation.

The inner space, shown in Figure 4 corresponds to the place where the hammam was installed after the Portuguese left Safi. The narrow door that can be observed on the left side, leads to the lateral chapel and to the present access of the cathedral. On Figure 4 also modifications introduced by the Muslim community can be observed. This modification correspond to the closing of the windows with masonry, as shown in Figure 4a. Also the space beneath the arch of the north-west elevation was closed with a masonry wall, as seen in Figure 4b and c. This part is believed to have been completely open towards the main corps of the ancient church. A detail of the encounter of the arch, the column and the infill wall can be observed in Figure 4c.

In Figure 5 general aspects of the Cathedral are shown. The alley that limits with the Cathedral is shown in Figure 5a. It presents the left side of the exterior wall of the Cathedral that can be seen from the Grand Mosque of Safi. The entrance of the cathedral is shown in Figure 5b and c. Again, a difference between the level of the street and the pavement of the ground floor of the Cathedral can be observed. In Figure 5d the lateral chapel is shown. The view is in the north-west direction in which (probably) the naves of the Cathedral were placed. This arch was not closed with a masonry wall like the main chapel was.

(a) (b) (c) (d)

Figure 5: General aspects: (a) alley and exterior wall of the Cathedral; (b) north-east façade of the lateral chapel; (c) present entrance to the ruins of the cathedral, through the lateral chapel; and (d) view of the lateral chapel in the direction of the former nave.

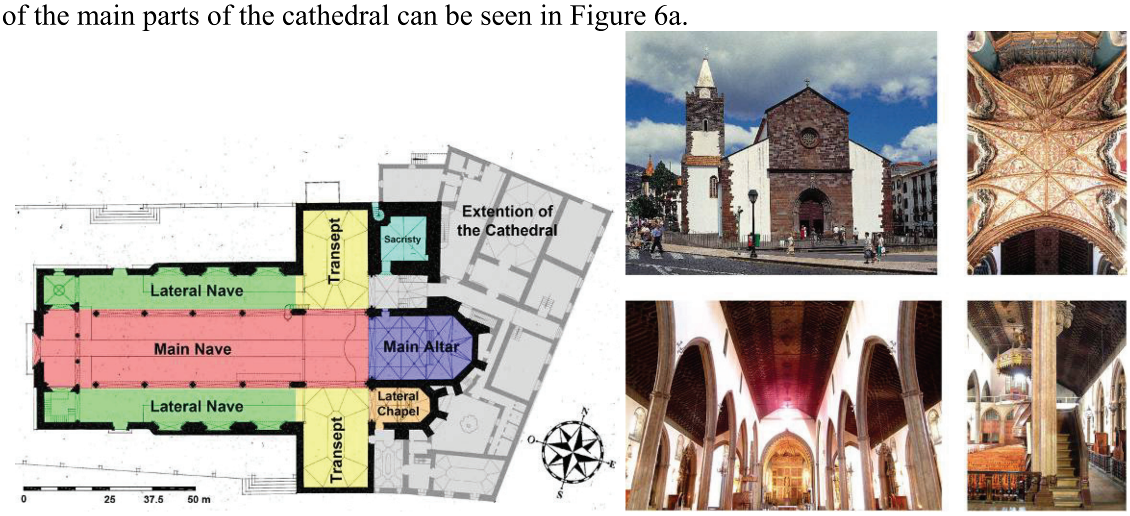
As it was shown in Figure 2, the space that belonged to the naves is today occupied by dwellings with thick stone masonry walls, concrete pavements and is covered with wooden roof-terrace structures. Also a big public bath and toilets are available in that zone.

The ground floor of the rest of the housings surrounding the original structure is at least 1.5 m higher than the Cathedral ground floor. These buildings are structurally connected with the Cathedral, guaranteeing a significant interlocking between the structural ensembles.

THE FUNCHAL CATHEDRAL

Funchal is located on the Portuguese island of Madeira. The island is located 720 km from the West African coast, almost on the same latitude of Safi. The construction took place between 1493 and 1516. The Funchal Cathedral still has its original Manueline structure intact and which has not been substantially modified or restored. Some minor restoration works took place during the decade of 1940 [3].

Each nave of the three which compose the main corps of the temple is separated by a series of columns which are joined through five arches in the longitudinal direction. The arches start at the façade and run along until they meet the wall of the abside. Both the main and the lateral chapels are vaulted. Next to the cathedral on the western part, an independent array of housing and courtyards which serves to the cleric uses the space of the remaining block. The distribution of the main parts of the cathedral can be seen in Figure 6a.



(a) (b)

Figure 6: The Funchal Cathedral [3]: (a) distribution in plant of ground floor; and (b) views of the cathedral.

The majority of the walls are rendered with lime plaster, as can be seen in Figure 6b. In the interior all walls are plastered, except the stone arches. This was also probably the case of the Safi Cathedral. The vault of the main chapel is highly decorated. It has ribs which cross the vault transversally and diagonally and there are keystones where the ribs encounter, just as in the case of the Safi Cathedral (see Figure 6b). The roof which covers the naves is an ornamented light wooden roof. In the central nave the roof is pitched, while the ones of the lateral naves are lower and have a single slope. The roof of the main altar and the lateral chapel is flat, consequently the extrados of the vault is carrying an infill, recently provided.

It is important to point out that horizontal metal ties have been installed along the main nave on the upper part of the longitudinal arches in 1971 [3]. This work was probably done to prevent future damages due to earthquakes, since the columns and arches are very slender. In this case the ties are intended to make the two longitudinal systems work jointly, since the light wooden roof cannot be considered as a stiff diaphragm and therefore a high probability of out-of-plane collapse persists.

Comparing the Safi Cathedral and the Funchal Cathedral some similarities and differences arise. On one hand, the proportion and configuration of the main chapel and the lateral chapels are the same. Also both probably had a main nave and two lateral naves with a light wooden roof, but there are no signs of transept in the remains of the Safi Cathedral. A tower close to the main altar of the Safi Cathedral is also missing. The original roof of the Safi Cathedral and the lateral chapel are lost. However it is possible to state that the lateral chapel of the Safi Cathedral also possessed a vault, as the stone ribs of the rise of the arches in the corners, and some others in the subsisting walls are partially in situ.

INSPECTION AND DIAGNOSIS WORKS

Prior to the design projects, inspection and diagnosis works were carried out to evaluate the stability of existing buildings, to detect possible structural damages, and to guide the design processed in terms and recommendations for actions to be undertaken.

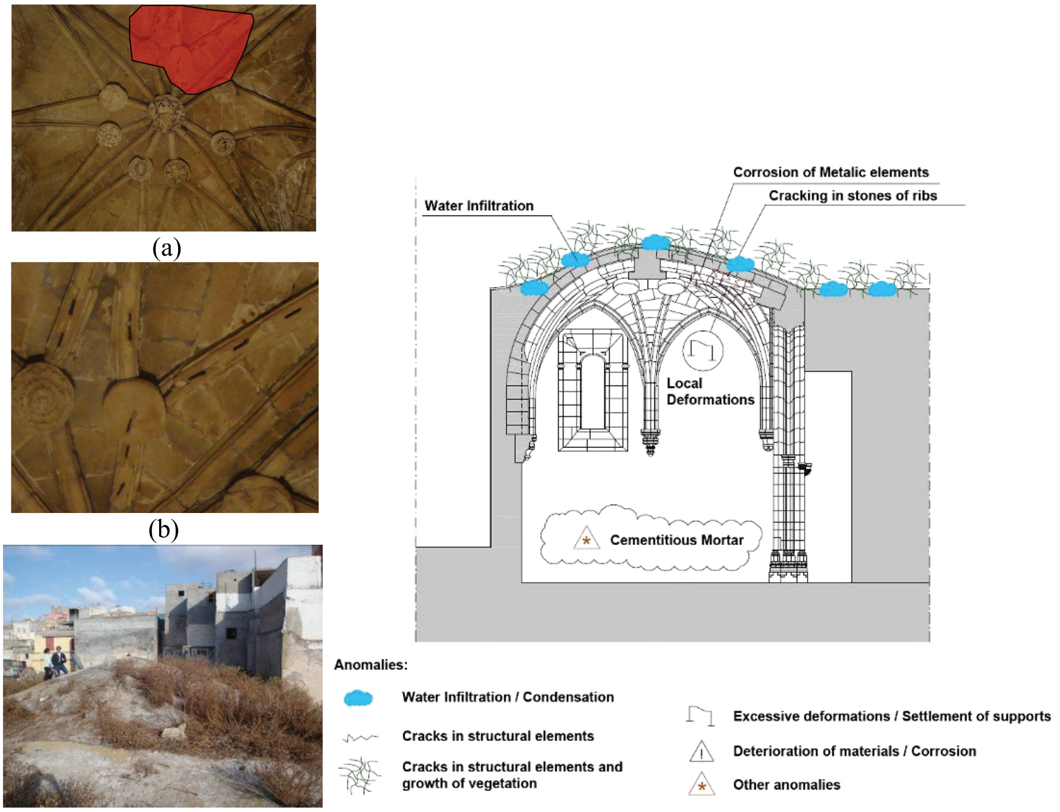
To achieve these objectives, a visual inspection and nondestructive testing between 13 and 15 May 2009 were carried out [2]. In order to obtain more information about the structural behavior and the state of conservation of the Cathedral, two non-destructive tests (NDT) were carried out at the main chapel: dynamic test and sonic tests. During the dynamic tests also environmental parameters were measured. Additionally, laboratory test were carried out to determine the type of mortar used originally in the construction of the Cathedral.

Visual Inspection

The inspections were pursued in what remains from the original construction of Safi Cathedral and in the surrounding buildings to identify the typology of the structural elements, the materials and the existing damages of the structure. This inspection followed a three-dimensional survey of the structure made by Miranda [4]. Attention was only given to the original parts of the Cathedral, since part of the remaining structures are going to be demolished, according to the existing rehabilitation project. Inspection windows were done on the external wall in order to determine the thickness and the morphology of the walls.

During the visual inspection no relevant cracks in the masonry walls which are going to be maintained by the new rehabilitation project were detected. Regarding the vault of the main chapel, a zone with large vertical displacements was observed (see Figure 7a). This zone limits with an old perforation of the vault which was introduced for the hammam chimney.

The existence of a chimney which crossed the vault exactly at one of the main-stones of the ribs was already documented in 1929 by the General Head Office of Arts and Historical Monuments of France [1]. The consequence of this alteration is the opening of some joints of the ribs and the opening of cracks in stones, justifying the earlier insertion of metal clamps as reinforcement. The deformed zone (marked in red) and the metallic reinforcement are shown in Figure 7b. However, the corrosion of the clamps has provoked the expansion of the metallic elements, generating new cracks and aggravating the stability of that zone of the vault. It can also be observed that the ribs of the vault do not present a perfect symmetry. This is most probably a construction defect.



(c) (d)

Figure 7: Main chapel vault: (a) general view with deflected zone (red); (b) detail of metallic strengthening works; (c) extrados of the vault with vegetation that induces cracks in the cover material; and (d) the damage map.

The vault is covered from the outside with a cement layer that has large cracks, in which even vegetation grows, see Figure 7c. These defects permit the infiltration of water, washing out fine material and deteriorating the lime mortar of joints of the vault and walls beneath. Finally, Figure 7d summarizes the anomalies of the main chapel which were previously mentioned.

Dynamic test of the vault

A dynamic test was performed on the extrados of the vault. The objective of this test is to gain valuable information about the dynamic behavior of the structure. The aim is to identify more relevant modal frequencies and modes, damping or to be able to estimate the rigidity of the structure. These results can help to calibrate numerical models, such as FE models, through a process called numerical optimization. In this particular case study, taking into account that the geometry of the structure is known, the FE model can be calibrated for the following purposes: locate zones with possible anomalies, determine for different levels of excitation dynamic coefficients and to determine boundary conditions of the structure.

(a) (b) (c)

Figure 8: Dynamic tests: (a) location of accelerometers; (c) accelerometers on the perimeter of the vault; and (d) accelerometer on top of the vault.

The dynamic test consisted in the measurement of accelerations in different points of the extrados. Accelerometers were installed with the configuration shown in Figure 8. The source of vibration was environmental vibrations (wind, traffic pedestrians, etc) and which has the characteristics of white noise. The vibrations were recorded for 10 min with a sample rate of 200 Hz.

The acceleration records were then processed through an output-only method, since no controlled vibration was induced to the structure. The data processing was done with a stochastic method known as Stochastic Subspace Identification (SSI) method. The result shows that the frequencies of the first 10 modes range from 5.2 to 11.7 Hz. Damping ratio ranges from 0.9% to 4.7%, with an average value equal to 3.2%.

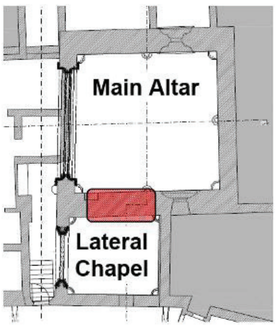
Sonic tests on one wall

The sonic test is done with an instrument which posses two transducers. One of them emits mechanical impulses while the other one is able to perceive them. If the geometry of the test sample is known (for example the thickness of a wall), the velocity of propagation of the signal within the sample can be determined.

These results can be used to determine the kind of material the test sample is composed of, to determine the quality of the material and/or to find anomalies in the sample. It can also be used to test in-situ the effectiveness of restoration works, such as grouting of masonry walls. Figure 9a shows some average values for a variety of materials. With exception of steel, the range of values of sonic velocities, due to the dispersion of the quality and density of materials, is high.

Type of material	Sonic velocity [km/s]
Steel	5.8
New masonry	1.0 - 3.0
Old masonry	0.4 - 2.5
Concrete	4.2 - 5.2
Timber	3.5 - 6.0
Stone	2.0 - 5.0

(a)



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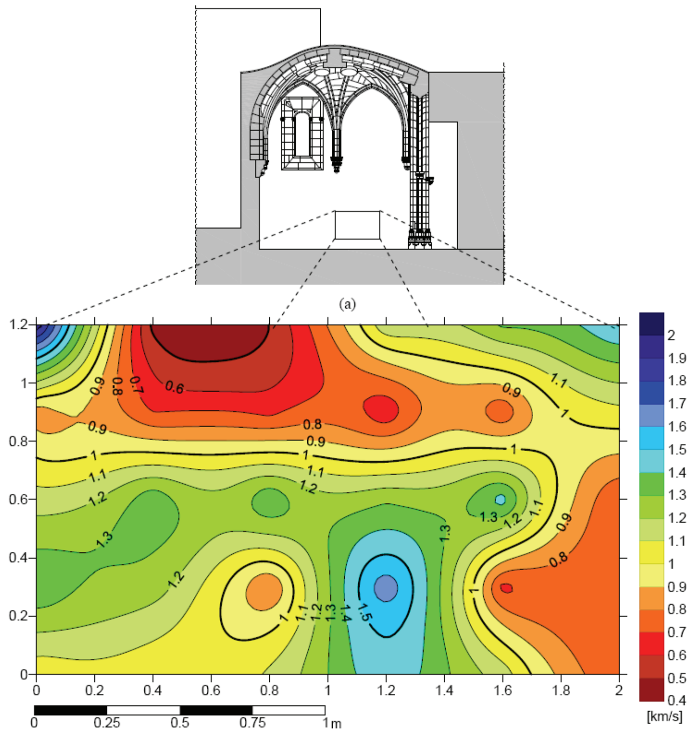


(c)

Figure 9: Sonic test of the wall: (a) common values for sonic velocities; (b) location of measurement grid; and (c) sonic velocity map.

In the case of the Safi Cathedral, the sonic test was used to determine the actual state of walls. Three sonic tests were performed: two on two stones in the interior of the main chapel and one on the wall that separates that compartment from the lateral chapel. Here, only the results on the masonry wall will be presented.

To analyze the state of conservation of the walls, an area of 2.0 × 1.5 m and 50 cm over the ground floor was chosen. Figure 9b shows the location where the sonic test was carried out. The velocities were measured on a 40 cm horizontal and 30 cm vertical mesh. The transducers were positioned on opposite sides of the wall, permitting direct measurements. On each point, 10 measurements were taken from both sides. The mean value of the velocities of propagation inside the wall measured on a same spot was then taken as the real value.

Figure 9c shows a velocity map of the mean velocities of propagation of the wall. The velocities range from 0.5 to 2.0 km/s, with a mean value of 1.1 km/s. The mean value corresponds to an expected value for old masonry walls. Nevertheless the difference between the maximum and minimum values indicates the existence of cavities inside the wall. This fact also indicates that the wall corresponds to a three leaf wall with smaller stones or gravel in its center.

Conclusions of the Inspection Works

The remains of the Safi Cathedral present various similarities with the dimension and in plant distribution of the Funchal Cathedral. Therefore, the Funchal Cathedral can serve as a model for the restoration works with respect to esthetics and structural features.

The laboratory results indicate that the stones are from calcaric origin and that the mortar used is lime mortar of high purity.

In general, no important damages of the structural elements (such as walls or vault) where observed during the visual inspection. However, some deficiencies have to be addressed.

The joints which present cementitious mortar should be removed and substituted by lime mortar, similar to the original one. This will eliminate compatibility problems and permit a more homogeneous behavior of the structure.

The extrados of the main altar vault has been covered by a cement layer. This layer presents large cracks which host vegetation. These cracks also permit the filtration of water and the subsequent washing out of fine material and degradation of mortar of the vault and supporting walls. Humidity was detected in the environment of the main chapel, but no efflorescence on walls nor pavement were spotted during the visual inspection, which could indicate high salt content in the subsoil. To avoid the deterioration of the structural members, it is recommended to eliminate the vegetation in the cracks and to protect meanwhile the extrados of the vault and the upper part of the walls from water until a definite solution is adopted. The restoration project proposes the solution for this problem for the long term situation.

The results of the dynamic tests reveal that the analyzed structure presents high natural frequencies. This is probably due to the support of the surrounding constructions next to the main altar.

The sonic tests and the perforation of the lateral wall revealed the existence of voids inside the masonry wall which divides the lateral chapel and the main one. These voids could be filled through injection grout of lime mortar, to consolidate the walls. The zones have to be determined previously, since an uncontrolled grouting is undesirable and very probable because of the similar masonry of the adjacent structures.

STRUCTURAL INTERVENTION

The structural intervention will be carried out at two levels. Firstly to do the structural rehabilitation of the remaining parts (main chapel, lateral chapel and exterior wall) from the original structure, and secondly to build a new structure for the naves, its roofs and the roofs for the vault and lateral chapel. The design was assisted by the use of FE models.

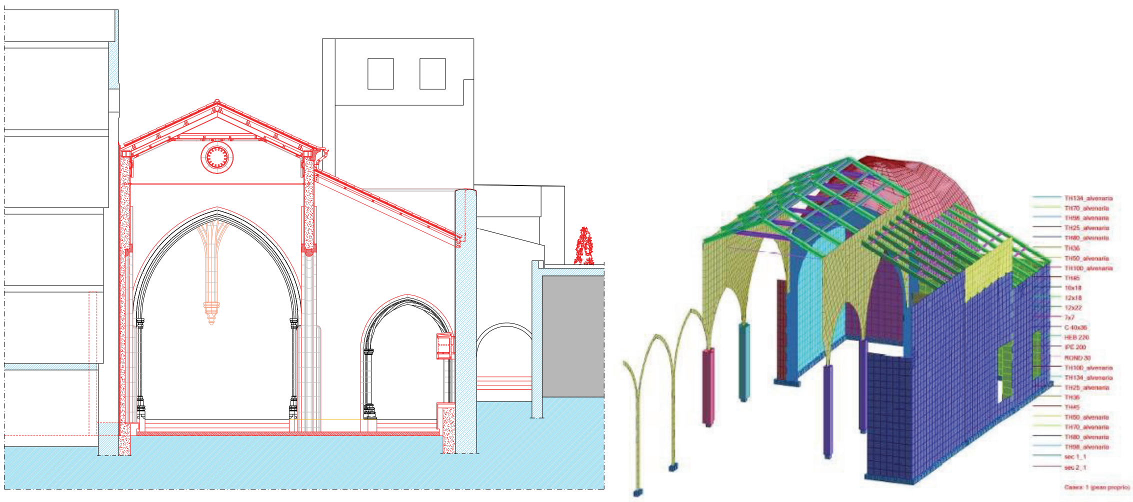
Starting with the existing parts to consolidate, the intervention will accomplished the following tasks: (a) removal of existing plasters or mortars done with cement; (b) consolidation of existing walls that have a high void ratio controlled with sonic velocity tests, by injecting lime-grouts; (c) consolidation of the vault by closing the cracks and removing the damage metallic clamps and substituting by new ones in stainless steel; (d) consolidation of the curved arch in the lateral chapel; (e) filling the extrados of the vault with a lightweight material with expanded clay and lime based mortars; and (f) introduction of a small buttresses in the arch of the main chapel to absorb the lateral impulse.

The consolidation of the arch of the main chapel is of particular difficulty, since it presents a pronounced deformation in the middle span, being probably supported by the masonry wall built under the arch to create the hammam. The demolition of this wall will be monitored, specially the movements of the vault. The displacements will be compared with the FE model, allowing an even guarantee safety during the works.

Concerning the new added structure, for the lateral arches and walls of the new naves, it was proposed walls with 40 cm thickness, supported by rather slender pillars with 6 m height and 40×40 cm^2 cross section. The bearing material is reinforced concrete. The use of slenderness the pillars creates a difficulty level in the project, aiming at achieving a feasible solution. It should be stressed that Safi is settled in a seismic zone; therefore the seismic performance was also considered in the design.

To support the roof of the naves, it was proposed a steel frame structure with high stiffness in order to reduce the buckling problems of the slender concrete pillars. The frame structure with HEB220 cross sections has a strong continuity/connection with the reinforced concrete walls. This solution helps to reduce the slenderness of the pillars to acceptable values, ensuring the distribution of horizontal actions (wind and earthquakes), especially in the perpendicular direction to the side walls of the naves. With this solution, the out-of-plane deformation is closer to a fully connected frame, rather than a pined connection.

The roof of the lateral nave and lateral chapel is made of a timber structure that ensures structural safety for the actions of gravity and wind, as well as catching the existing side wall which is admittedly the original wall of the cathedral. Figure 10 shows a cross section of the proposed structural intervention and an image of the FE model used for safety evaluation.



(a) (b)

Figure 10: Structural intervention: (a) cross section; and (b) FE model.

A simpler beam elements model was also developed in order to evaluate the slenderness lengths of the pillars. The slenderness were compared with code requirements and used to calculate second order effects. A more complex model was developed to evaluate stresses and displacements due to gravity, seismic and wind loads. Finally, a third and more complex model will be built in future studies in order to take into account the material non-linear effects.

CONCLUSIONS

The rehabilitation project of the Safi Cathedral has been a long discussion process in its urban and architectural frames, and from the coordination point of view with engineering. Figure 11 presents the architectural proposal.

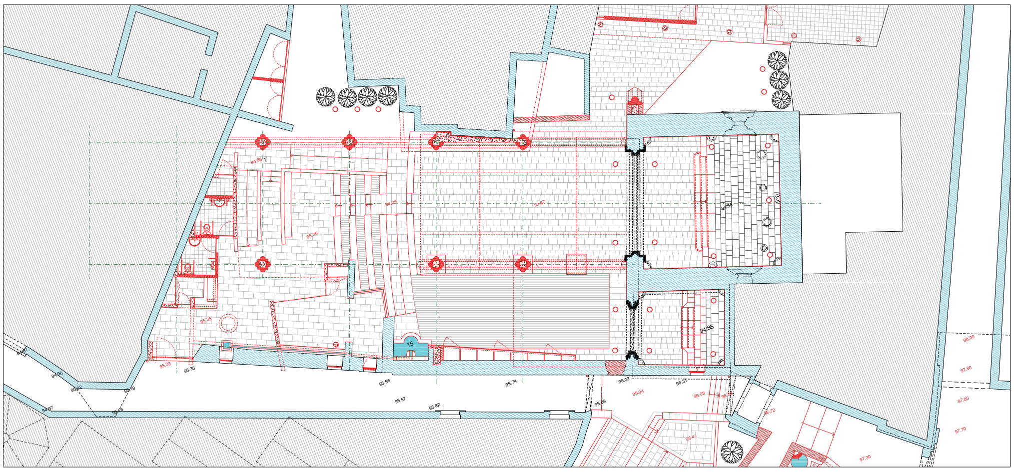
In fact, it would only worth to operate in this patrimony if it could sustain a practical goal for the intervention, beyond the heritage interest itself and despite its greatness.

Local quality of life was much diminished, and the project constitutes the leitmotiv to enhance sanitary and economic conditions for the people living in the quarter of the old Cathedral.

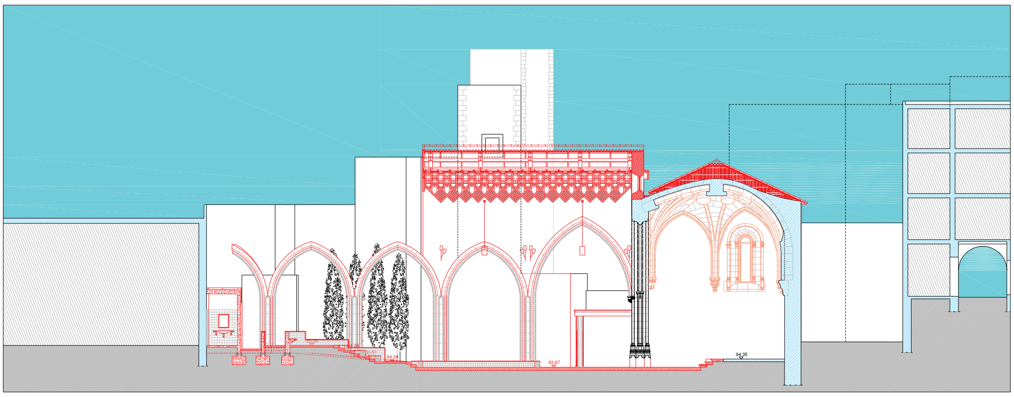
Without any capability to continue living in such bad dwelling zone, some dozens of persons were moved to new residential conditions, and the area is available to implement the project, with new urban infrastructures being constructed to serve a very dense zone of the old city.

Today, the place of the remains and the space that belonged to the ancient Portuguese Cathedral, in the middle of the historic Safi, being the project a real opportunity to make the improvements on the quality of life of the place.

The aggregation of very strong reasons from the historical, monumental and tourism point of view are the basis for the rehabilitation in course, coordinating and equating technical procedures and decisions, in order of a better preservation of a so important heritage.



(a)



(b)

Figure 11: Architectural proposal: (a) plan; and (b) longitudinal section.

AKNOLEGEMENTS

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